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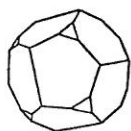
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Character, genesis and tectonic setting of igneous rocks in the Sistan suture zone, eastern Iran

V. E. CAMP AND R. J. GRIFFIS

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Igneous rocks in the Sistan suture zone have characteristics that can be correlated with important tectonic events. A Late Cretaceous ocean basin is recorded by ophiolites now exposed in numerous mélangé zones. Subduction beneath the Afghan block is indicated by Late Cretaceous-Paleocene calc-alkaline volcanics. Collision of the Lut block with the subduction complex in the middle Eocene produced widespread deformation and was followed by the emplacement of late Eocene-early Oligocene calc-alkaline granitic batholiths that probably formed by widespread anatexis of marine sediments. A dominantly Oligocene magmatic event is represented by widespread alkaline volcanics and minor intrusions that appear to be related to major transcurrent faults. Miocene calc-alkaline activity was limited to sporadic volcanism in the north and minor intermediate intrusions farther south. These units are largely undeformed and not related to any major faults. The youngest magmatic event is recorded by late Miocene-Pliocene mafic flows that are weakly alkaline, clearly related to right-lateral faults and probably were derived from a deep crustal or upper mantle source.

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The Phanerozoic history of Iran has been dominated by a series of complex plate interactions that are only partially understood. In northern Iran, destruction of the Paleo-Tethys was a consequence of pre-Liassic collision and suturing of central Iranian microcontinental fragments (or fragment) with Laurasia north of the Alborz Mountains (Stocklin 1977; Sengor 1979; Wensink & Varekamp 1980). In southern Iran, consumption of the Neo-Tethys led to Maastichtian (Berberian & King 1981) or Miocene (Bird et al. 1975; Sengor & Kidd 1979) collision of the Arabian shield with the central Iranian platform along the Main Zagros Thrust (Stocklin 1977). In southeastern Iran, east of the Zagros suture, northward subduction of ocean floor in the Gulf of Oman has continued beneath the Makran since Late Cretaceous time (Farhoudi & Karig 1977). The least understood area of plate interaction is the inner ophiolite sub-belt (Stocklin 1977) of central and eastern Iran (Fig. 1), where thick piles of deep-water marine sediments occur with common exposures of ophiolite and mélangé (Delaloye & Desmons 1980). Here there is a distinct lack of field and analytical data to assess accurately any model of plate interaction.

The Sistan intracontinental suture zone of eastern Iran (Figs. 1 and 2) represents a narrow, short-lived strip of oceanic lithosphere consumed

in the Senonian and Paleogene and in part, obducted during an Eocene period of continental collision (Tirrul et al. in press). This paper presents new information regarding the field relationships, age, petrographic, and chemical characteristics of the igneous rocks in the Sistan suture zone. Their nature and petrogenesis are interpreted in light of the tectonic environment in which they were produced.

This study is based on information gathered in 1977-1978 during an extensive regional mapping and mineral evaluation program in eastern Iran. The mapping aspect of the program was conducted by Watts, Griffis and McOuat Limited of Toronto, Canada under contract to the Geological and Mineral Survey of Iran (GMSI). Maps at 1:50,000 scale with explanatory notes as well as 1:250,000 scale maps with more comprehensive reports have been submitted to GMSI for publication. Important aspects of the geology and the tectonic history of the Sistan suture zone are summarized by Tirrul et al. (in press).

General geology and tectonic framework

Late Cretaceous to Tertiary rocks of the Sistan suture zone separate two blocks of continental

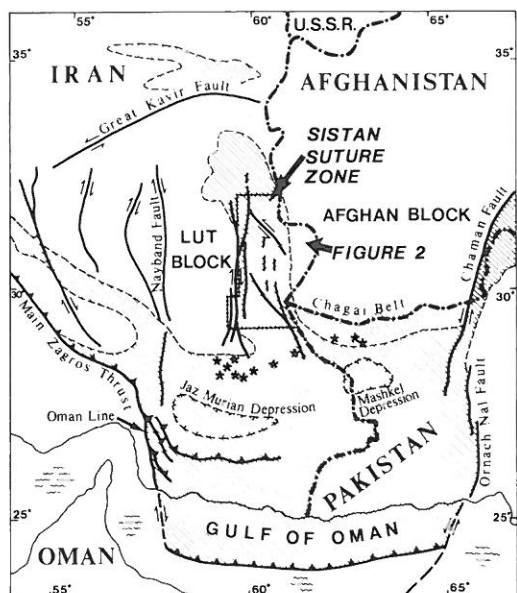


Fig. 1. Location of the Sistan suture zone, the Lut and Afghan blocks, and surrounding physiographic and geologic features. Ruled area represents Late Cretaceous to Tertiary accretionary prism-flysch basin deposits and incorporated ophiolite and mélangé. Asterisks denote Quaternary calc-alkaline volcanoes north of the Makran Ranges.

character: the Lut block to the west and the Afghan block to the east (Fig. 1). Early (?) Cretaceous rifting separated the continental landmass into the two blocks and created a small ocean basin that eventually closed through north-east subduction and collision by middle Eocene time. The blocks are presently reunited along the Sistan suture zone.

The western border of the Afghan block is buried in the map area (Fig. 2) by the Neogene sediments in the Helmand Depression, but it is believed to lie close to the foot of the East Iranian Ranges, a broad mountainous area largely coincident with the Sistan suture zone. The eastern edge of the Lut block is in part marked by the East Lut fault system (Freund 1970; Huber 1978), a zone of north-northeast trending right-lateral transcurrent faults marking the western boundary of the map area (Fig. 1).

The suture zone features two distinct geological terranes (Fig. 2): the Neh-Ratuk complex and the Sefidabeh basin, interpreted as an accretionary prism and 'forearc' basin, respectively (Tirrul et al. in press). The accretionary prism is subdivided into two subparallel zones termed the Neh

and Ratuk complexes. The Neh complex occurs along the western part of the suture zone in the map area considered here (Fig. 2); most of the Ratuk complex lies north of the map area, although scattered exposures of Ratuk mélangé occur in the Sefidabeh basement. The accretionary prism contains a wide variety of rock types including Senonian to Maastrichtian ophiolite, Cretaceous to Eocene phyllite, and Paleogene terrigenous marine sedimentary rocks. These rocks are in various degrees of disarray, commonly comprising a mélangé of diverse rock types, but they occur also as large fault-bounded blocks of uniform lithology. Maastrichtian and Paleogene marine sediments of the 'forearc' basin onlap the complex to the west. However, the present contact between the two terranes is generally tectonic. Unlike the highly tectonized accretionary prism, the Sefidabeh basin contains a coherent stratigraphy in which some formations can be traced the full length of the map area. The 'forearc' basin contains a volumetrically small but important succession of calc-alkaline flows, pyroclastics, and volcanoclastic derivatives interbedded with terrigenous clastic rocks and limestones.

Three phases of Cenozoic deformation have been recorded in marine sediments in the Sefidabeh basin (Tirrul et al. in press). The first two occurred between early Eocene and early Miocene time. The oldest phase produced upright folds with an approximate easterly trend which are best displayed in the northern half of the map area. The second, more dominant phase produced a regional system of conjugate strike-slip faults and related folds corresponding to an east-northeast direction of maximum horizontal shortening. Fold interference is common, with the first folds generally being re-folded about north-northwest trending axial surfaces. In some cases, coeval folding is evident from mutual interference of both fold orientations. The third phase of deformation is of Pliocene-Quaternary age and has resulted largely in right-lateral strike-slip movements which are spectacularly displayed along the East Lut fault system. Maximum slip along these faults is 50 to 70 km and it has been suggested that this latest deformation is related to the indentation of central Iran by the Arabian shield in late Tertiary time (Tapponnier & Molnar 1976; Tirrul et al. in press).

Since Early Cretaceous the Sistan suture zone has undergone a rather complex history marked by changes in the tectonic environment and cor-

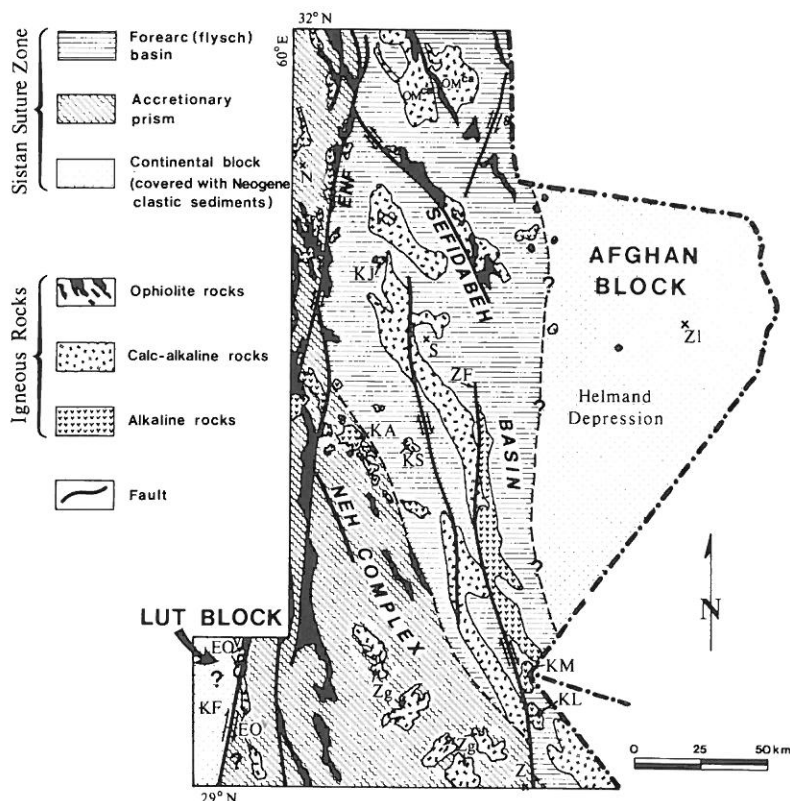


Fig. 2. Geologic subdivisions of the Sistan suture zone and generalized outcrop pattern of igneous rocks in the map area. Place names are: Nehbandan (N), Sefidabeh (S), Zabol (ZL), and Zahedan (Z). Faults noted are: East Neh Fault (ENF), Kahurak Fault (KF), and Zahedan Fault (ZF). Intrusions are: Zahedan granites (Zg), Kuh-e Lar (KL), Kuh-e Malek Siah (KM), Kuh-e Seyasteragi (KS), Kuh-e Assagic (KA), Kuh-e Janja (KJ), and the area encompassing the Rud-e Shur intrusions (RS). The only calc-alkaline volcanics designated are OM^{ca} and EO^{ca}; all other calc-alkaline outcrops are KP^{ca} and intercalated volcanoclastics of the Sefidabeh basin. All alkali volcanic outcrops are OM^{al} and Ng^{al} undifferentiated. The area between the Afghan and Lut blocks is broadly rugged and often referred to as the East Iranian Ranges.

responding changes in the stress regime. Rifting, subduction, ophiolite emplacement, continent-trench collision, uplift, and at least three phases of Cenozoic deformation have been responsible for the present configuration of the suture zone. Several magmatic episodes have been recorded throughout its dynamic history. The igneous rocks produced by these events are described below, and their genesis is discussed as it relates to the tectonic environment in which they were formed.

Igneous rocks

The oldest igneous rocks of the map area are the Late Cretaceous ophiolites of the subduction complex which mark the basement of most of the

flysch stratigraphy. They are not described in detail here because they formed in a separate tectonic environment distinct from the other igneous rocks of the region. The ophiolite lithologies are the product of pre-Senonian rifting and the development of the Late Cretaceous ocean separating the Lut and Afghan blocks. They are present in the mélanges and although generally highly faulted, there are several complete northeast-facing ophiolite sections. The ophiolite basaltic rocks are typically tholeiitic where spilitization has not altered their original chemistry and mineralogy (Tirrul et al. 1980).

The remaining volcanic rocks of the area are integral parts of the regional stratigraphy, and are thus given age designations based on their stratigraphic position. They are further differen-

tiated on the basis of chemistry, petrography, and tectonic setting. From oldest to youngest they include Cretaceous–Paleocene volcanics (KP^v), Eocene–Oligocene volcanics (EO^v), Oligo–Miocene alkali volcanics (OM^{al}), Oligo–Miocene calc-alkaline volcanics (OM^{ca}), and Neogene volcanics (Ng^v).

The intrusive rocks defined by this study are named from their type localities (Fig. 2). They occur as small separate intrusions (e.g. Kuh-e Seyasteragi and Kuh-e Janja), as a series of large and small intrusions spread over a wide area (e.g. Zahedan granites and Rud-e Shur diorites), and as intrusive-vent complexes of variable rock types (e.g. Kuh-e Assagie and Kuh-e Lar).

Age

Nineteen K–Ar radiometric age determinations obtained from mineral separates and whole rock analyses (by Teledyne Isotopes, Inc.) are shown in Table 1. The decay constants used were: $K\lambda_{\beta} = 4.962 \times 10^{-10}/\text{yr.}$, $K\lambda_{\epsilon} = 0.581 \times 10^{-10}/\text{yr.}$, $K^{40}/K = 1.167 \times 10^{-4}$ atom ratio. Age dates were determined for representative samples from all igneous rocks except the Cretaceous–Paleocene volcanics (KP^v). However, these volcanics are interbedded with and overlain by limestone units of Late Cretaceous and early Paleocene ages, as determined from microfossil identifications.

Chemistry

Major element analyses (except for sodium) were made on 169 samples by X-ray fluorescence spectroscopy using pressed pellet techniques (analyses by the Department of Geology, University College, Swansea, U.K., and Bondar-Clegg, Limited, Ottawa, Canada). Sample counts were compared with internal standards of similar composition and appropriate absorption corrections were applied. Trace elements and sodium were determined from atomic absorption spectroscopy and wet chemical analyses respectively (by the Department of Geology, Swansea). CIPW norms and major and trace element analyses for selected samples are given in Table 2. Oxide variation diagrams (Figs. 3 and 4) are plotted from data in which major element and volatile components are normalized to 100%. The estimated coefficients of variations for the oxides are summarized in Table 2. Although considerable effort was made to analyse only fresh mate-

Table 1. K/Ar age determinations.

Igneous unit	Sample number	Method	Age (m.y.)
<i>Volcanics</i>			
Ng ^v	G-1809	Whole rock	3.8±0.2
	G-2138	Whole rock	5.7±0.3
	G-2155	Whole rock	7.3±0.5
OM ^{ca}	G-802D	Hornblende	23.8±6.2 ¹
OM ^{al}	A-45	Whole rock	27.0±1.9 ²
EO ^v	G-791B	Whole rock	37.1±1.9 ²
<i>Intrusives</i>			
Kuh-e Janja	G-1590	Hornblende	16.5±2.0
Kuh-e Seyasteragi	C-391	Hornblende	19.2±1.4
Kuh-e Assagie	M-1333	Biotite	27.5±2.0
Kuh-e Malek Siah	C-348	Hornblende	27.2±4.0
	C-349	Hornblende	28.8±3.5
Kuh-e Lar	C-188b	Biotite	27.8±3.0
	C-200	Whole rock	32.0±1.6
	C-188a	Whole rock	32.8±3.0
Zahedan granites	G-1081	Biotite	31.4±1.6
	G-1076	Biotite	32.2±1.6
	G-1078	Biotite	32.9±2.0
	G-1077	Biotite	33.6±1.7
Rud-e Shur	G-2178	Whole rock	44.6±2.2 ²

¹ The analytical results for this sample are not good. Regional evidence suggests that this shallow pluton is late Early or Middle Miocene in age (10–18 m.y.).

² Results are suspect because of minor alteration.

rial, some of the more silicic members of the Cretaceous–Paleocene calc-alkaline volcanic group (KP^v) are pyroclastic and hence may contain alteration products that will mask the original chemistry to some degree. Details of the analytical results can be made available upon request.

The igneous rocks of the region may be combined into two chemical groups, as illustrated by the total alkalis/silica ratio (Fig. 3) which differentiates the rocks of the region into those with alkalic and subalkalic affinities. The *alkalic group* (Fig. 3A) includes the Kuh-e Lar/Kuh-e Malek Siah and Kuh-e Assagie intrusive complexes as well as the Oligo–Miocene (OM^{al}) and Neogene (Ng^v) mafic to intermediate volcanics. The *subalkalic* or *calc-alkaline group* (Figures 3B and C) includes the Zahedan granites, the Kuh-e Janja, Kuh-e Seyasteragi, and Rud-e Shur intrusions, and the Cretaceous–Paleocene (KP^v), Eocene–Oligocene (EO^v), and Oligo–Miocene (OM^{ca}) intermediate to silicic volcanics. The subalkalic group can be further differentiated by plotting the chemical data on AFM and alumina vs. normative plagioclase diagrams (Figs. 4A and

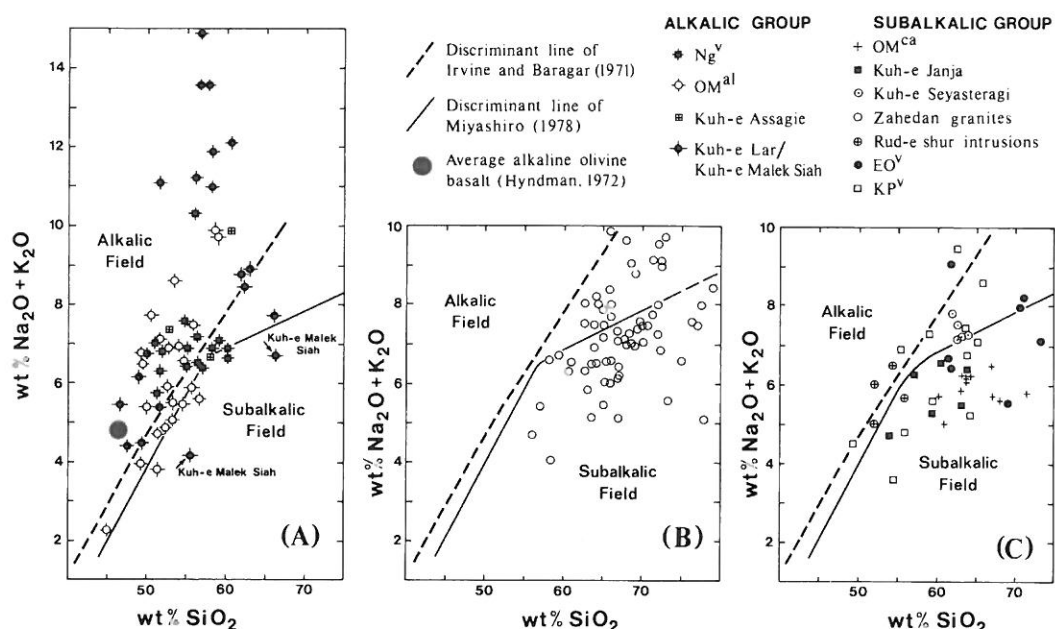


Fig. 3. Total alkalis vs. silica diagram. Discriminant curves divide intrusive and extrusive units into those that plot as alkaline [A], and subalkaline ([B] for Zahedan granites; [C] for all others).

B). All subalkaline rocks plot in the calc-alkaline field, with only KP^v straddling the tholeiite/calc-alkaline discriminant curve of both plots (Fig. 4B). Representative analyses for rock types found in both the alkaline and calc-alkaline groups are given in Table 2.

Fieldwork, supplemented by chemistry, has established both broad time-stratigraphic variations in volcanism and cross-cutting relationships in most intrusions. However, a detailed chemical synthesis of lava lineages and fractionation trends within individual volcanic fields and intrusive complexes must await more detailed investigations.

Field and petrographic characteristics

The plutonic complexes of the area were intruded within a relatively short time interval from late Eocene to early Miocene, a span of approximately 30 m.y. The calc-alkaline intrusions (Rud-e Shur, Zahedan granites, Kuh-e Seyasteragi, and Kuh-e Janja intermediate porphyries) cut strongly folded Maastrichtian to Paleogene marine turbidites and are unrelated to any apparent major deep-seated faults. However, the Kuh-e Assagie alkali intrusions and volcanics may be

related to a complex, deep-seated northeast-dipping fault marking the contact of the Sefidabeh basin and Neh complex. Similarly, the Kuh-e Lar complex may be related to the Zahedan right-lateral strike-slip fault (Fig. 2.) The alkaline intrusions also differ from the calc-alkaline plutons in that they are intrusive complexes of several cross-cutting rock types representing local centres of volcanic activity.

Most of the calc-alkaline volcanics of the area were extruded in a subaqueous environment as indicated by interbedded marine sediments. The only exception is the relatively young Kausar volcanic field (OM^{ca}) that was formed subaerially in the northern part of the map area. All the alkaline volcanics were extruded in an emergent, subaerial environment. As with their intrusive counterparts, the calc-alkaline volcanics appear unrelated to any major deep-seated structures, whereas the alkali volcanics are particularly abundant only in close proximity to the major transcurrent faults of the region.

Petrographically, rocks of the calc-alkaline and alkaline groups differ significantly, particularly with regard to mineral content. The calc-alkaline group generally contains intermediate to felsic intrusions, flows and pyroclastic rocks whose

Table 2. Selected analyses of igneous rocks from the East Iranian Range.

Major & minor oxides (wt %)	Calc-alkaline						Alkaline				
	1 ¹ (G-767)	2 (J-1916)	3 (V-399)	4 (B-2063)	5 (G-1077)	6 (G-1703)	7 (N-728)	8 (V-329)	9 (V-693)	10 (M-1333)	11 (C-188)
SiO ₂ ²	62.88	64.22	56.05	63.47	68.26	62.10	58.55	54.16	54.50	60.20	57.21
Al ₂ O ₃	17.42	17.08	15.43	13.98	15.94	17.30	16.94	13.85	15.94	16.90	21.19
TiO ₂	0.66	0.77	0.92	0.94	0.48	0.41	0.63	0.75	1.87	0.48	0.30
Fe ₂ O ₃	4.20	3.00	4.75	7.02	0.96	1.32	3.34	7.77	6.39	4.00	2.91 ³
FeO	0.48	1.04	4.28	0.80	1.99	1.76	2.00	1.72	0.40	0.30	—
MgO	1.26	1.15	4.00	1.82	2.25	3.02	2.41	6.36	3.37	1.40	1.13
CaO	3.68	5.07	6.16	2.97	2.59	4.54	4.45	5.07	7.58	4.12	1.92
Na ₂ O	3.33	4.43	2.90	4.11	3.23	4.60	7.00	4.76	5.81	3.88	5.14
K ₂ O	3.41	1.81	1.96	3.27	4.07	3.11	2.82	3.88	1.73	6.31	8.42
MnO	0.11	0.02	0.13	0.10	0.01	0.03	0.14	0.16	0.09	0.08	0.05
P ₂ O ₅	0.24	0.27	0.74	0.36	0.11	0.21	0.31	0.38	1.05	0.20	0.32
S	—	—	—	—	—	—	—	—	—	—	0.20
H ₂ O ⁴	1.79	1.56	2.69	1.67	0.71	1.33	1.09	2.85	1.14	1.58	0.49 ⁵
CO ₂	0.03	0.00	0.01	0.00	0.00	0.57	0.39	0.10	0.03	1.80	—
Original Total ⁶	99.49	100.42	100.03	100.49	100.60	100.30	100.07	101.81	99.90	101.25	99.28
Trace elements (ppm)											
Cr	11	33	25	1	33	39	15	320	38	10	—
Ni	8	26	12	6	45	38	15	79	58	11	—
Cu	32	18	169	0	22	9	3	53	64	50	—
Zn	48	68	81	94	35	51	104	78	113	73	—
Pb	17	31	14	73	65	32	44	39	51	47	—
Rb	98	61	39	93	193	110	71	73	20	255	—
Sr	308	560	945	525	360	1,528	1,118	672	4,470	844	—
Y	20	67	31	65	63	26	35	47	25	38	—
Zr	164	289	141	120	156	179	151	99	339	270	—
Nb	16	7	1	3	9	3	5	3	19	19	—
CIPW normative minerals (wt%)											
AP	0.56	0.63	1.72	0.84	0.25	0.49	0.72	0.87	2.45	0.46	0.75
PY	—	—	—	—	—	—	—	—	—	—	0.38
IL	1.27	1.47	1.75	1.78	0.91	0.78	1.20	1.41	3.57	0.91	0.58
OR	20.38	10.72	11.58	19.31	23.91	18.37	16.68	22.69	10.27	37.07	50.24
AB	28.49	37.56	24.53	34.75	27.16	38.89	54.53	32.71	47.85	32.63	24.05
AN	—	21.42	23.29	10.03	12.06	17.36	6.48	4.91	12.36	7.73	7.51
C	2.23	—	—	—	1.77	—	—	—	—	0.83	0.91
MT	2.20	2.18	2.18	2.18	1.38	1.91	2.18	2.18	2.18	2.16	2.20
DIWO	—	0.84	0.99	0.98	—	0.08	4.65	7.05	7.65	—	—
DIEN	—	0.49	0.47	0.37	—	0.06	2.57	3.99	4.70	—	—
DIFS	—	0.32	0.50	0.63	—	0.01	1.90	2.77	2.52	—	—
OLFO	—	—	—	—	—	—	2.41	8.19	2.61	—	1.99
OLFA	—	—	—	—	—	—	1.96	6.27	1.55	—	0.14
HYEN	3.17	2.39	9.49	4.16	5.57	7.46	—	—	—	3.47	—
HYFS	3.05	1.57	9.97	7.16	2.06	1.45	—	—	—	2.64	—
Q	20.31	19.32	10.37	15.39	24.22	10.72	—	—	—	6.79	—
Nc	—	—	—	—	—	—	2.57	3.86	0.81	—	10.76
CC	0.07	—	0.02	—	—	1.29	0.89	0.23	0.07	4.06	—
Differentiation index (OR + AB + Q = DI)	69.2	67.6	46.5	70.0	75.3	68.0	73.8	59.3	58.9	76.5	59.3

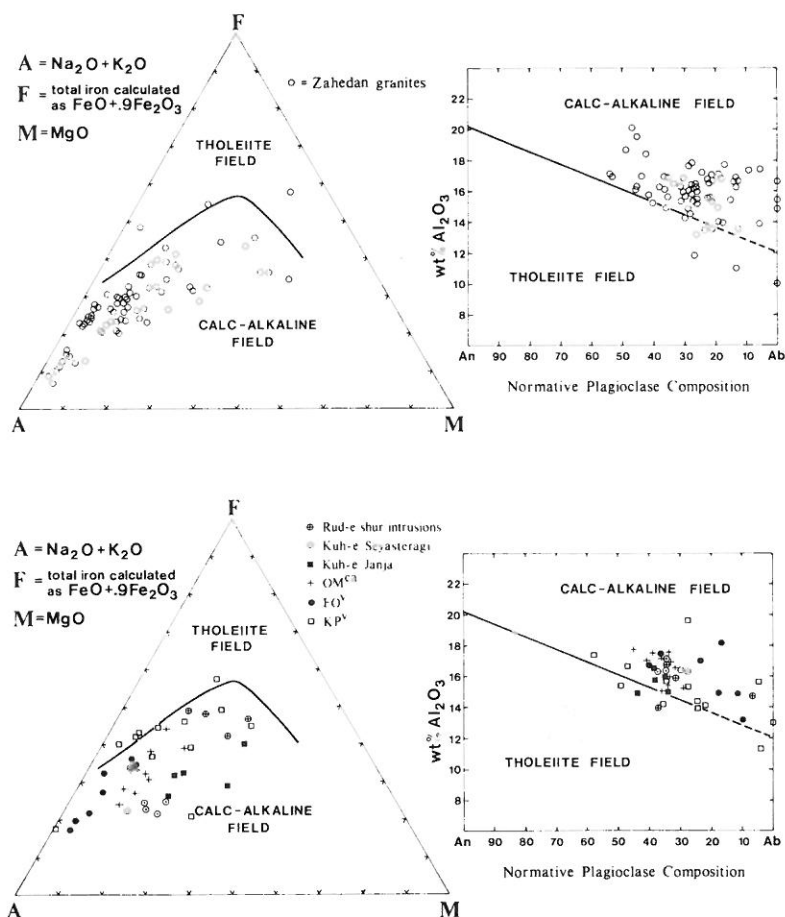


Fig. 4. AFM and alumina vs. normative plagioclase diagrams used to differentiate subalkaline igneous rocks (of Fig. 3B and C) into those having calc-alkaline and tholeiitic affinities; [A] for Zahedan granites, [B] for remaining subalkaline samples. Discriminant curves are from Irvine & Baragar (1971).

¹ Analyses number 1 through 11; original sample numbers given in brackets: 1) andesite (EO¹), 2) dacite (OM^{ca}), 3) andesite (KP¹), 4) ash flow (KP¹), 5) granitoid (Zg), 6) andesitic porphyry (KS), 7) mugearite (OM^{ca}), 8) alkali basalt (OM^{ca}), 9) hawaiite (Ng¹), 10) monzonitic intrusion (KA), 11) syenodiorite (KL).

² Analyses indicated here are the original analytical data. Analyses 1 through 9 done at the Department of Geology, University College, Swansea under the direction of R. D. Lowman and A. W. Bloxam. Reported coefficients of variation are as follows: SiO₂ ± 0.7%; Al₂O₃ ± 0.22%; TiO₂ ± 0.02%; Fe₂O₃ ± 0.2%; MgO ± 0.2%; CaO ± 0.2%; Na₂O ± 0.2%; K₂O ± 0.2%; MnO ± 0.02%; P₂O₅ ± 0.02%; H₂ ± 0.03%; CO₂ ± 0.03%; general coefficient of variation reported as ± 8% overall. Analysis 11 was done by Bondar-Clegg and Company Ltd., and the coefficients of variation will be similar to those indicated above. It should be emphasized that although it is fairly standard practice to report analyses and normative calculations to the second decimal place, the coefficients of variation indicate that, for most of the major elements, the second decimal place is meaningless.

³ Total Fe reported as Fe₂O₃.

⁴ Analyses 1 through 10 were analysed for H₂O⁺, and H₂O⁻, the sum of which are reported as H₂O.

⁵ For this analysis the H₂O actually represents the loss on ignition and will likely include minor CO₂.

⁶ For normative calculations the Fe₂O₃ content above 1.50% has been arbitrarily set at 1.50 and the remaining Fe₂O₃ recalculated as FeO. Data are normalized to 100% and then recalculated to give the weight percent of normative minerals. All calculations done at Department of Geology, University College, Swansea under the direction of D. Watkins.

compositions are typical of subalkaline suites. Plagioclase, amphibole, and clinopyroxene are common, along with variable amounts of olivine, hypersthene, orthoclase, and quartz depending on the acidity of the rock type. The alkaline group contains mafic to intermediate intrusions and flows. The rocks may contain any of the minerals typical of the calc-alkaline group, although hypersthene and quartz are relatively rare. Characteristically alkalic minerals are found in several rock types: nepheline, sodalite, leucite (?), melilite, analcite, kaersutite, and rare aegerine-augite. A brief description of the field and petrographic characteristics for each volcanic group and intrusion is given below.

KP^v

Calc-alkaline flows, pyroclastics, and their associated epiclastic derivatives (KP^v) are interbedded with Cretaceous and Paleocene marine sediments of the Sefidabeh basin. The oldest of these volcanics are Maastrichtian andesite and subordinate basaltic andesite flows. These units are 10 to 70 m thick, some are pillowed, and they are invariably plagioclase-phyric. The phenocrysts are typically euhedral (0.5 to 1.5 cm in diameter) with a compositional range from An₃₀ to An₆₅. Amphibole and/or augite can constitute up to 50 % of the phenocryst phase. The flow matrix is largely devitrified glass with abundant plagioclase microlites.

Stratigraphically higher in the flysch sequence are Maastrichtian-Paleocene to Paleocene subaqueous ash-flows, tuffites (Schmid 1981), and autobrecciated, spherulitic rhyolite flows. Rare mafic to intermediate flows are interbedded in the upper part of the flysch stratigraphy. The pyroclastic rocks include lapilli-ash tuffs with graded bedding and varying proportions of vitric, crystal, and lithic fragments. They are commonly compacted (indurated or incipiently welded), and in many cases welded. Glass shards are invariably devitrified and altered to chlorite and clay mineraloids. Analyses 3 and 4 in Table 2 are fairly typical of the units.

Although regional correlations are tenuous, the flysch belt, with associated volcanics, appears to continue north of the map area where it splits into two zones lying west and east of the Ratuk complex (Maurizot 1979; Tirrul et al. in press). It continues southeast of the map area, across the

Iran-Afghanistan-Pakistan triple point and along the southern rim of the Helmand Depression in Pakistan.

EO^v

Andesitic flows, pyroclastics, and minor mafic flows (EO^v) occur in the southwest corner of the map area (Fig. 2). Welded tuffs occur in the more northern exposures. These volcanics are interbedded with Eocene nummulitic limestones and immature volcanoclastics. Their total thickness is estimated to be several hundred metres. The volcanics occur within a tectonic zone along the eastern margin of the Lut block and they are tentatively correlated with Lut block volcanics to the northwest (Kluyver et al. 1978) which are similar in age, chemistry, and appearance.

The andesitic flows are usually porphyritic with a plagioclase phenocryst phase (generally in the range An₃₅-An₅₀) being very dominant (commonly 20-40% of the rock volume). Clinopyroxene (augite) phenocrysts are often minor constituents and amphiboles more rare. The aphanitic to vitric groundmass consists of devitrified glass and feldspathic (quartzo-?) material containing abundant pleochroic silicates that are largely unidentified. Very fine-grained iron oxides are invariably present and alteration products (chlorite, epidote, calcite, clay and sericite) are widespread in most samples. Many of the units are lithic and crystal tuffs containing variable amounts of quartz, biotite, plagioclase and potassium feldspar. The best exposures of the welded tuffs are reddish to pink weathering and display compaction and flow features both in outcrop and in thin-section. The less common mafic flows appear to be fairly massive basalts containing phenocrysts of plagioclase (An₆₀-An₇₀), hypersthene, and augite in a dark brown glassy matrix. Analysis 1 in Table 2 is a typical andesite from this area.

At the southernmost end of the map area, near the Kahurak fault (Fig. 2), the EO^v units are in fault contact with a thick section of beautifully pillowed, coarsely porphyritic basalt interbedded with immature sandstones and conglomerates. The units are also interbedded with fine-grained limestones that have been tentatively dated as Paleocene. The volcanics have no apparent relationship with EO^v volcanics and in appearance they are most similar to some of the KP^v sections in the north part of the map area. However,

because we have insufficient information on these units they have been excluded from the accompanying maps and discussions.

OM^{ca} and OM^{al}

After filling and emergence of the Sefidabeh basin, the Sistan suture zone was a centre of sub-aerial volcanism during the Oligo-Miocene. Volcanism during this time was dominantly alkalic (OM^{al}), but calc-alkaline volcanism (OM^{ca}) occurred in the north part of the map area near Kuh-e Kausar and farther north in the Gazik region (Maurizot 1979).

The mildly deformed calc-alkaline volcanics (OM^{ca}) are preserved in broad structural depressions where intermediate to felsic flows, pyroclastic rocks, and lahars are piled to an estimated thickness of 1,500 m. The flows are generally dacitic, but range in composition from basaltic andesite to rhyodacite. They are commonly auto-brecciated, phyrlic to microphyric, and display trachytic and hyalopilitic texture. The groundmass is devitrified glass, and the phenocryst phases are plagioclase (An₃₀–An₅₀), basaltic hornblende, and rare clinopyroxene. In some areas the volcanic pile is intruded by numerous felsic plug domes which crop out as resistant spires with relief up to 500 m. Analysis 2 in Table 2 is representative of OM^{ca} dacites.

The Oligo-Miocene alkali volcanics (OM^{al}) crop out discontinuously throughout the map area. They consist of mafic to intermediate flows and minor pyroclastic rocks interbedded with a variegated succession of volcanic conglomerate, immature volcanoclastic arenite, and mudstone. They are often strongly folded and faulted and rest unconformably on rocks as young as early or middle Eocene.

The greatest percentage of flows are olivine basalt, basalt, and hawaiite (mugearite is present in small amounts), but the most undersaturated flows are picrite basalt, olivine melilite basalt, and olivine nephelinite. Their mafic mineralogy includes olivine, augite, and rare aegerine-augite. Kaersutitic and/or barkevikitic amphibole occurs in many of the more felsic flows. Na-plagioclase is a common constituent of the groundmass, and slightly more calcic-plagioclase (An₃₀–An₅₅) is a common phenocryst phase. Nepheline is present in several flows and is sometimes the dominant groundmass mineral. Subhedral sodalite is common in the groundmass of

many of the flows which crop out along the western rim of the Helmand Depression north of Zahedan (Fig. 2). Anhydrous analcite, commonly associated with zeolite amygdulites, is a typical late magmatic phase. Common resorption of primary minerals and numerous reaction relations suggest that the alkali volcanics crystallized under non-equilibrium conditions.

Although many flows are moderately- to strongly-alkalic, many others are chemically transitional between alkalic and subalkalic suites (Fig. 3A). However, the presence of several flows containing typical alkalic mineralogy has led us to designate the OM^{al} unit as being essentially alkalic. Analyses 7 and 8 in Table 2 are representative of this unit.

Ng^v

Flat-lying flow remnants of Neogene volcanics (Ng^v) form buttes and mesas that dot the surface of the map area. These volcanics lie unconformably on all other units except Plio-Pleistocene and Quaternary deposits. The flows are weakly alkalic and range in composition from olivine basalt to mugearite, but most are hawaiite. Remnants usually consist of one flow (less than 100 m thick) made up of numerous flow units 2 m to 3 m thick. Several of the mesas have gentle inward-dipping concentric weathered ridges, giving them a saucer-shaped appearance.

The flows are usually pilotaxitic and microphyric with sodic (?) amphibole as the phenocryst phase. Plagioclase (An₄₀–An₅₅) occurs in the groundmass with either amphibole, clinopyroxene, or less commonly, olivine. Analcite may be present as a late magmatic (deuteric) product. Analysis 9 in Table 2 is typical of these young flows. The whole rock K-Ar age determinations (Table 1) are in the range of 3.8–7.3 m.y. which corresponds approximately with middle Pliocene to late Miocene.

As indicated in Fig. 3A, the Ng^v flows are not strongly alkalic. Although most lie in the alkali field designated by Miyashiro (1978), they straddle the discriminant curve of Irvine & Baragar (1971). Furthermore, the abundant alkali mineralogy that characterizes the OM^{al} flows is not present in Ng^v flows. However, we favour an alkali designation for these units based on the common occurrences of normative nepheline. It is also worth noting that virtually all of the Ng^v flows have a TiO₂ content greater than 1.4 wt%

whereas the older alkali flows (OM^{al}) almost invariably have less than 1% TiO₂. The high TiO₂ content of the Ng^v units is also characteristic of the very young alkalic basalts in the Lut block, close to the Nayband fault (Conrad et al. 1972; Kluyver et al. 1978).

Rud-e Shur intrusions

Mafic to intermediate dykes are widespread in the folded flysch sequences east and north of Kuh-e Janja in the northern part of the map area. These largely vertical dipping intrusions have northerly trends and, in some cases, are up to 20 m wide and traceable along strike for several kilometres. Most, however, are less than 10 m wide and traceable on surface for a few hundred metres to 1–2 km. Their resistant character and black weathering appearance makes them clearly visible in the field and on most air photos.

In the field it was often possible to distinguish intrusions of intermediate and mafic composition. The intermediate dykes are typically medium-grained, equigranular, and contain minor visible quartz. The mafic dykes are usually fine- to medium-grained, diabasic, and often contain small (<0.75 cm) phenocrysts of intermediate to calcic plagioclase. In thin-section the intermediate dykes are dominated by plagioclase and clinopyroxene (usually <15 modal %) but quartz is quite conspicuous; in a few cases the feldspar rims contain wormy intergrowths of quartz (myrmekite). The mafic units contain felty aggregates of plagioclase (An₃₀–An₅₀) and intergranular clinopyroxene (augite) that is commonly chloritized.

The age of these dykes is not well established. One whole-rock K–Ar age determination yielded a middle Eocene age (44.6 m.y., Table 1) which is plausible but reexamination of the sample material indicated minor alteration effects and hence the radiometric date may not be reliable. The dykes certainly predate the widespread strike-slip faulting in the area and, in places the dykes have been weakly folded. Because of the age uncertainties they have been given a broad Paleogene designation on maps of the region.

The chemistry of these units is quite similar to some of the arc volcanics (KP^v) referred to earlier and it is possible that the intrusions were feeder dykes to the KP^v effusives.

Zahedan granitoids

A variety of granitic rocks are widely exposed in a large, northwest-trending belt immediately west of Zahedan. The resistant intrusions stand well above the surrounding countryrock which is dominated by weakly metamorphosed marine clastic sediments of the Neh complex. Individual intrusive bodies and complexes vary in size from batholiths to much smaller stocks and dykes. Where observed, contacts with the countryrock are invariably sharp; metamorphic aureoles are not well-developed although in the most eastern intrusion (Kuh-e Lashak), a dark hornfels aureole is clearly visible on air photographs but is far less obvious in the field. The intrusive bodies are generally concordant with sedimentary sequences.

Most of the intrusions are actually a complex of several phases although each complex is dominated largely by an intermediate to felsic main phase. The main phase is medium grained, usually coarsely foliated, and frequently contains abundant but small xenoliths of metasediments from the Neh complex. Other phases include both highly foliated, more mafic units often found around the margins of the much larger main phases and younger, irregularly shaped felsic bodies usually within the interior of the main phases. Late phase pegmatites are present in several of the batholiths but absent in most. One of the features common to virtually all of the intrusive areas is the presence of a large number of generally north-trending dykes. These are most spectacularly displayed at the Kuh-e Lashak batholith where myriads of dark weathering dykes make up approximately 20% of the igneous rocks. Most of the dykes are intermediate in composition although there are many late stage mafic units that crosscut all others. These dykes are also widespread in adjacent metasediments.

Most of the intrusive phases have a relatively simple mineralogy dominated by plagioclase (An₂₀–An₄₀), biotite, quartz, and potassium feldspar in varying proportions. Petrographically the main phases lie close to the granodiorite-quartz monzonite-granite triple point (Streckeisen 1973). The more felsic phases are real granites although some are close to being alkali granites and usually have less than 15 modal % biotite. The highly foliated, more mafic phases commonly contain 25–40% mafics (dominantly biotite and minor amphibole) and lie close to the grano-

diorite-tonalite boundary. The late phase pegmatites are dominated by perthitic feldspar, quartz, and lesser plagioclase; coarse biotite and some muscovite are usually present and fine- to coarse-grained, black tourmaline crystals are abundant in many exposures.

As shown in the accompanying Table 1, K-Ar radiometric dates on biotite samples from several different areas in the intrusive belt indicate solidification ages in the general range of 31–33 m.y. for the main phase intrusions. The general field characteristics suggest that most of the intrusions crystallized at moderate depths and were emplaced in a relatively passive manner. There are no indications that the intrusions have any volcanic equivalents. These intrusions contain no significant metallic mineralization.

Kuh-e Lar/Kuh-e Malek Siah intrusions

Kuh-e Lar is a very prominent and rugged mountain northeast of Zahedan, close to the Pakistan border. It is a late Oligocene volcanic-intrusive complex with features indicative of a collapsed caldera (Chance 1981). Nearby, at Kuh-e Malek Siah, there are widespread intermediate sills that have similar characteristics to some of the Kuh-e Lar intrusive phases although there are no apparent effusive centres. The 8 × 5 km Kuh-e Lar complex is hosted by a very thick sequence of Late Cretaceous to Paleogene marine sediments that are part of the Sefidabeh basin. Exposures are extremely good, but access to many parts of the caldera structure are limited by steep cliffs. Much of the complex is covered by dark weathered mafic volcanic flows and pyroclastics but a variety of intrusive phases are contained within the eroded core of the caldera. The earliest intrusive phases are relatively mafic whereas the younger intrusions are progressively more felsic and generally described in the field as monzonites and syenites. Much of the Kuh-e Lar complex is cross-cut by numerous north-northeast trending fracture zones and some of these are closely associated with copper mineralization which is found in several parts of the complex.

The petrography of these varied intrusions will only be briefly described. The early mafic phases contain abundant intermediate plagioclase (An₃₅–An₄₅) and acicular amphibole phenocrysts set in a matrix dominated by alkali feldspar. Later syenites contain abundant clinopyroxene (principally augite) and minor olivine pheno-

crysts in a matrix dominated by alkali feldspar. Still younger syenites contain phenocrysts of sanidine, clinopyroxene, plagioclase (An₂₅–An₃₅), and phlogopite in a finer-grained feldspathic matrix. In places this phase displays a crude but distinctive layering. Very late-phase intrusions contain variable amounts of pink sanidine and plagioclase set in a finer-grained matrix of mafic minerals (phlogopite, clinopyroxene, amphibole) and feldspar. Compositionally these cover a range of quartz monzonite to syenite or quartz syenite.

Whole rock samples yielded K-Ar age dates of approximately 32 m.y. for Kuh-e Lar whereas biotite and amphibole separates from Kuh-e Malek Siah and Kuh-e Lar yielded approximate K-Ar ages of 27–28 m.y. The younger ages are considered to be more reliable. Because of similar radiometric ages and close proximity, we have generally regarded the magmatic activity at Kuh-e Lar and Kuh-e Malek Siah as being equivalent. However, the units at Kuh-e Malek Siah are not as highly alkaline as most of those at Kuh-e Lar (Fig. 3A) and, in fact, the two events may be distinct.

Kuh-e Assagie intrusive complex

This intrusive-volcanic complex occurs as a prominent series of hills in the central part of the map area. The complex consists largely of ill-defined intermediate flows and shallow plutons; more felsic units (dacitic) are occasionally encountered. Brecciated zones are well exposed in several areas. One large exposure of coarse monzonitic porphyry occurs along the margin of the complex. Andesite and trachyandesite flows with some interbedded tuffs are exposed in numerous small outcrops in the immediate vicinity of the main complex. These flows are quite distinct from the flat-lying more mafic flows (Ng^v) that cap many of the hills in this general area. Although the Assagie complex is largely enclosed by weakly metamorphosed sediments of the Neh complex, a similar shallow level plutonic complex is located nearby at Kuh-e Chahok (approximately 20 km southeast of Kuh-e Assagie) where the countryrock is unmetamorphosed, but highly folded, early Tertiary flysch of the Sefidabeh 'forearc' basin.

Most of the units are dominated by plagioclase of intermediate composition. Sanidine is present in numerous trachyandesites but apparently ab-

sent in other flow units. Biotite is the most widespread mafic mineral although amphibole and clinopyroxene are observed in many samples. Most units contain no observable quartz but some of the more felsic units contain up to 10–15% modal quartz, in some cases, as a minor microphenocryst phase. Accessory, fine-grained iron oxides and apatite are scattered throughout most samples. The monzonite porphyry features coarse potassium feldspar phenocrysts, finer-grained flakes of fresh biotite, and a medium- to fine-grained feldspathic matrix.

The Kuh-e Assagie intrusive activity has been given a late Oligocene age on the basis of a 27.5 m.y. K-Ar determination from a biotite sample of the monzonite porphyry (Table 1). We think this complex was probably a significant vent area which has now been largely eroded. In the field it appears to be more like the Kuh-e Lar caldera complex rather than the younger intermediate intrusions such as the nearby Kuh-e Seyasteragi occurrences. Minor copper, lead, zinc, and silver are associated with this complex (Griffis et al. 1979).

Kuh-e Seyasteragi and Kuh-e Janja intrusions

Kuh-e Seyasteragi and Kuh-e Janja are rugged peaks in the north-central part of the Sefidabeh basin. They owe their existence to the resistant hornfels aureole surrounding less resistant, intermediate intrusive plugs. This type of intrusion occurs at numerous locations within highly folded flysch sequences and is invariably distinguished by the dark hornfels aureole. However, overall they are not volumetrically important, the largest intrusion being at Kuh-e Seyasteragi where it is approximately 5×1 km. Most occurrences of the intrusions are poorly exposed and many have minor copper mineralization associated with them (Griffis et al. 1979). In hand specimen, samples are generally described as medium- to fine-grained amphibole-plagioclase porphyries of intermediate composition. Although there are cross-cutting relationships evident in some exposures, the overall compositional range of most phases is not great.

The dominant minerals are intermediate plagioclase and green hornblende. The groundmass may contain quartz and potassium feldspar and trace amounts of iron oxide and apatite.

Potassium-argon age determinations on horn-

blende samples from Kuh-e Janja and Kuh-e Seyasteragi indicate Early Miocene intrusive ages (Table 1). Although the hornfelsing indicates that these plutons reached high crustal levels, there is no evidence to suggest that any of the intrusions fed volcanic vents.

Petrogenesis in view of changing tectonic environments

The oldest igneous rocks of the Sistan suture zone occur in a narrow belt trending northwest-southeast from the Cheshmeh-e Ostad volcanic complex along the Afghanistan border immediately north of the present map area (Maurizot 1979; Tirrul et al. in press). The belt separates shelf carbonates of the Afghan block to the northeast from the unconformably overlying flysch domain (Sefidabeh basin) to the southwest. The volcanics are probably the initial magmatic products of Cretaceous rifting.

After a small Late Cretaceous ocean basin had developed during the initial phases of flysch deposition, significant tectonic activity resulted in the emplacement of ophiolitic mélange and relatively intact slabs of ophiolite. The basement of the Sefidabeh basin is at least in part composed of an accretionary prism with incorporated ophiolite. Olistostromes with ophiolitic clasts are also present within the Sefidabeh basin succession. In the Neh complex the ophiolite rocks were probably emplaced by thrusting during subduction. The ophiolite lithologies are now present in the map area as northwest-trending mélange belts in the 'forearc' basin and as unoriented blocks of mélange in the Neh subduction complex (Fig. 2).

After emplacement of the ophiolite and ophiolitic mélanges, deep-water sedimentation, with only minor tectonic disturbances, continued in the Sefidabeh basin from the Maastrichtian through Paleocene and early Eocene time. The igneous rocks described in this paper originated after ophiolite emplacement, during and following flysch deposition in the Sefidabeh basin. The changing tectonic environment in which these extrusive and intrusive rocks originated is discussed below.

Calc-alkaline rocks

Fig. 5 illustrates the relationship between igneous and tectonic activity in the map area and

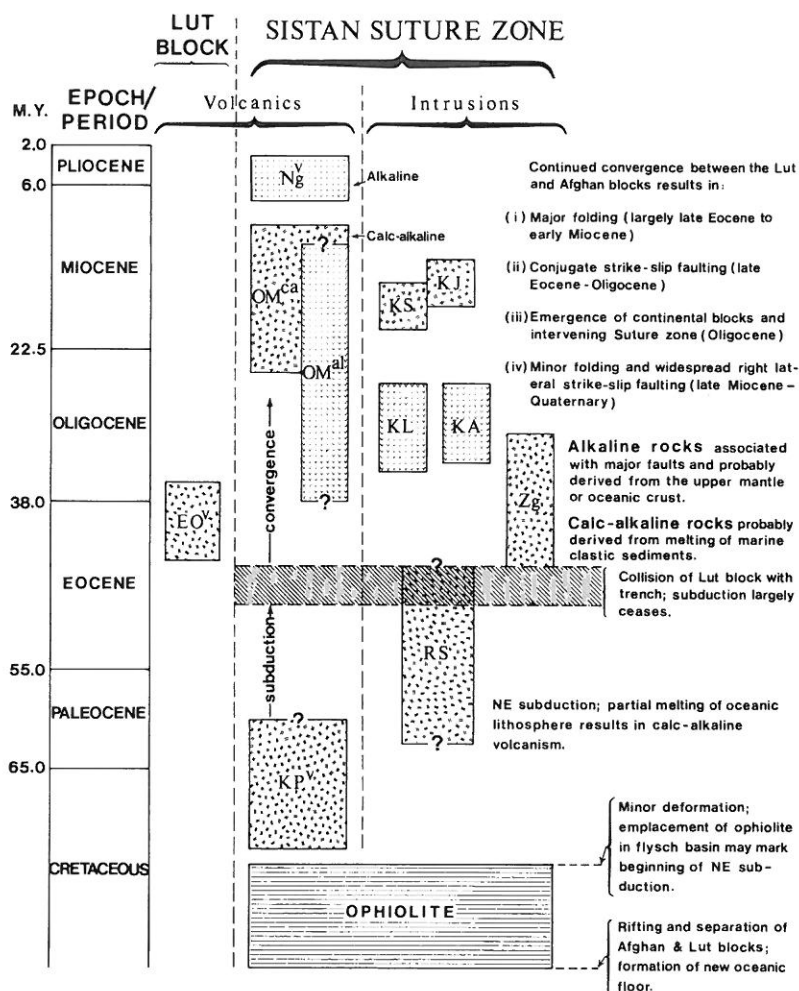


Fig. 5. Cretaceous through Tertiary magmatic events and their time relation to periods of deformation in the Sistan suture zone and that part of the Lut block in the map area. Volcanics are marked by their appropriate age designations whereas the intrusions are noted by KL, Kuh-e Lar; KA, Kuh-e Assagie; KS, Kuh-e Seyasteragi; KJ, Kuh-e Janja; RS, Rud-e Shur; Zg, Zahedan granites. Further discussion in text.

how the character of both has changed with respect to time. After Late Cretaceous ophiolite emplacement, the eastern Sefidabeh basin was the centre of sporadic subaqueous volcanic activity (KP^v) in the form of intermediate to felsic flows and pyroclastics. Volcanism was generally calc-alkaline, but several of the basaltic andesite flows plot as tholeiitic on subalkaline differentiation diagrams (Fig. 4B), precisely what one would expect from typically immature island arc volcanism (Miyashiro 1974). We interpret these volcanics as being the effusive products of north-

east subduction beneath the Afghan block. An extensive magmatic arc was not produced, most likely because subduction was not very long lived. Rifting and the development of oceanic crust may have begun by the Late Cretaceous. By Maastrichtian time an accretionary prism had developed which clearly suggests that subduction had been active at least during this epoch. However, the subduction largely ceased by middle Eocene as a result of the collision of the Lut block and subduction complex. Thus, subduction may have only lasted 20–40 m.y.

The 'forearc' basin volcanics (KP^v) can be traced out of the map area to the southeast into Pakistan. Here they can be directly correlated with rocks of similar character and age: the Sinjrani (Upper Cretaceous) and Juzzak (Paleocene-Eocene) Formations (Jones 1961; Schmidt 1968; Sillitoe & Kahn 1977). These rocks occur along the southern margin of the Afghan block (Fig. 1) as a somewhat arcuate east-west trending belt (750 × 175 km) termed the 'eruptive zone' by Jones (1961) and the 'Chagai calc-alkaline magmatic belt' by Sillitoe & Kahn (1977). Most of the volcanism in the belt occurred in the Cretaceous as intermediate to felsic, subaqueous flows, pyroclastics, and marine transported volcanic debris of the Sinjrani Formation. The volcanics and intercalated sediments are intruded by granitic stocks and batholiths thought to be the plutonic equivalents (roots) of overlying effusive rocks (Vrendenburg 1901; Sillitoe & Kahn 1977). Near the end of the Cretaceous period the north Chagai belt began to emerge as a plateau with biohermal reefs (Humai Formation) peripheral to its shoreline (Jones 1961). As suggested by Sillitoe & Kahn (1977) and Sillitoe (1978), the Chagai belt represents an Andean-style magmatic arc which originated in the Early Cretaceous as a result of northward subduction beneath the Afghan block. The Cretaceous to Paleogene arc volcanics can thus be divided into two contiguous and coeval segments: those of the northwest-southeast trending Sefidabeh basin overlying oceanic crust west of the Afghan block (KP^v), and those of the east-west trending Chagai belt overlying continental crust along the southern rim of the Afghan block (Fig. 1).

The Sefidabeh basin closed by late Eocene as the Lut and Afghan blocks became sutured by continental collision due to northeast subduction. However, subduction of oceanic lithosphere continued south of the Afghan block in a zone bounded on the west by the Oman line in Iran, and on the east by the Chaman fault in Pakistan (Stocklin 1974; Stoneley 1974; Farhoudi & Karig 1977). Continued subduction has resulted in significant continental accretion of Late Cretaceous and Tertiary shallow marine sediments in the Makran Ranges (Ahmed 1969; Auden 1974; Falcon 1974) and the development of an east-west line of Tertiary to Quaternary calc-alkaline volcanoes north of the Jaz Murian (Iran) and Mashkel (Pakistan) Depressions (Fig. 1). The youngest of these volcanoes are Kuh-e Bazman, Kuh-e Taffhan, and Kuh-e Sultan, the lat-

ter being in the western Chagai belt (Gannser 1971; Girod & Conrad 1976; Conrad et al. 1977; Dupuy & Dostal 1978).

The Lut block was the site of significant calc-alkaline volcanism in middle Eocene to early Oligocene time (Jung et al. 1976; Huber 1978; Kluyver et al. 1978). The Eocene-Oligocene volcanics (EO^v) along the southeast margin of the Lut block that are shown in Fig. 2 are thought to be equivalents to the more widespread Lut block volcanism. The mechanism by which these volcanics were generated is not well understood.

By late Eocene-early Oligocene time, the Lut block underwent a period of uplift and consequent erosion (Berberian & Soheili 1973; Berberian 1974; Kluyver et al. 1978). Volcanism ceased, and little deposition occurred from Oligocene through Miocene time. As illustrated in Fig. 5, this orogenic phase of uplift corresponds with the approximate time of closure and emergence of the Sefidabeh basin. As the Lut continental block approached and collided with the subduction zone, northeast subduction probably ceased. However, convergence probably continued, resulting in epeirogenic uplift of the Lut block, the Neh accretionary prism, and the Sefidabeh 'forearc' basin. On a more regional scale, the epeirogenic movement corresponds with the approximate time of oblique collision of the western part of the Indian continent with Eurasia and initiation of the Chaman fault in Pakistan and Afghanistan (Stoneley 1974).

Most of the igneous activity in the Sistan suture zone occurred after closure of the ocean basin and after emergence of the accretionary prism and 'forearc' regions was well underway. The Rud-e Shur diorites and quartz diorites are the oldest known intrusive rocks of the area (Fig. 5). They are hosted by strongly folded Cretaceous flysch of the Sefidabeh basin but they also appear to be folded themselves. The whole rock age date sample (44.6 m.y.) may not be reliable and it is possible that they could have been feeders to the KP^v calc-alkaline volcanics and therefore may have had an origin similar to these arc-volcanics.

The Zahedan granitic intrusions represent an important period of calc-alkaline magmatism associated with the Sistan suture zone. Although the granitoids occur within the accretionary prism, there is little evidence to suggest that they are products of subduction. Heat flow models show a considerable depression of isotherms in downgoing slabs (Hasabe et al. 1970; Minear &

Toksöz 1970; Oxburgh & Turcotte 1970; Toksöz et al. 1971). Magmatic activity in trench environments is therefore considered unusual during periods of subduction (Echeverria 1980). Furthermore, radiometric age dates and field relations indicate late Eocene to middle Oligocene solidification ages for most of the major intrusions. Thus, their development coincides closely with the Lut block-trench collision and the subsequent period of continued convergence between the adjacent continental blocks which resulted in the intense folding and faulting that is widespread in the region. The tectonic setting, petrographic and geochemical characteristics of these granitoids indicate many similarities with 'S' type granites as described by White & Chappell (1977). These include such features as: (1) variable intermediate to felsic compositions, (2) lack of volcanic equivalents, and (3) lack of base metal and gold mineralization but widespread indications of tin enrichment usually associated with tourmalinization. The regional setting appears to be very similar to the late Carboniferous tin granites of southwest England (Mitchell 1974) as well as the Tertiary tourmaline granites of the Himalayas (Gannser 1974). Both examples feature continent-continent collisions and subsequent development of granites. The Zahedan granitoids also have many similar tectonic and petrological features to the early Tertiary plutons along the margin of the Gulf of Alaska (Hudson et al. 1979). There is little evidence to link the generation of the Zahedan granitoids with any subduction activity and we strongly favour their derivation as being the result of anatectic melting of marine sediments in the accretionary prism (Neh complex) during the period of collision and subsequent convergence (Fig. 5).

The relatively young post-tectonic, Miocene calc-alkaline intrusions (Kuh-e Seyasteragi, Kuh-e Janja) are generally very small and not definitely linked to any volcanic activity. They appear to be quite distinct from the Zahedan intrusions but could be related to the Miocene calc-alkaline volcanics (OM^{ca}) in the northeast corner of the map area (Fig. 2). They are not related to any apparent structures and their origin remains problematical. They would seem to be unrelated to subduction activity and therefore we assume they must be linked to the melting of predominantly young sedimentary material at depth within the 'forearc' basin or, more likely, in the underlying accretionary prism.

The only post-collision calc-alkaline volcanic

rocks of the map area are the localized Oligo-Miocene flows and pyroclastic rocks near Kuh-e Kausar (OM^{ca}). Their age and distribution suggest that they are not likely to be direct products of subduction. Since they are generally silicic to intermediate and not enriched in incompatible elements, they may represent melts produced by a relatively high degree of partial melting of sialic material (probably > 10%; Green 1968; Nicholls & Ringwood 1972). However, fractionation has played at least some role in their genesis, as noted by younger (fractionated) dacite to rhyodacite domes intruding older (parental) andesite to dacite flows and pyroclastics.

Alkaline rocks

Alkali volcanism began in the East Iranian Ranges only after cessation of northeast subduction and closure of the small ocean basin separating the Afghan and Lut blocks (Fig. 5). By late Eocene time the Lut and Afghan blocks were reunited along the Sistan suture zone, but subduction continued to the south along the east-west zone of the Makran, beneath both of the sutured continental blocks. Northward subduction has continued in the Gulf of Oman to the present time (Stoneley 1974; White & Klitgord 1976; Farhoudi & Karig 1977). One might argue that Cenozoic alkali volcanism in eastern Iran is the product of continued subduction and deep-seated partial melting of oceanic lithosphere. However, several lines of evidence discussed below suggest that this volcanism is not subduction-related.

Kuno (1966), with quantitative support by Dickenson & Hatherton (1967), first recognized that the alkalinity of island arc magmas increased along with increases in depth of the subduction zone and lateral distance away from trench axes. The minimum depth of alkali magma generation along a subducting plate, based on earthquake focal depths, is generally considered to be greater than 150 km (Ninkovich & Hays 1972; Keith 1978), but may vary, depending on the rate of plate convergence and the amount of water present (Miyashiro 1974). Such depths have not been verified for the descending slab underlying eastern Iran and western Pakistan. Hypocenters are widely scattered in the Makran region, and they rarely exceed 100 km even in the northern part (Berberian 1976). Furthermore, alkaline rocks associated with subduction-related volcanics tend to be K-rich or shoshonitic (Jakes &

White 1972; Morrison 1980), whereas most alkali rocks of the East Iranian Ranges are distinctly Na-rich. The only exception is at Kuh-e Lar, where several rock types are very rich in potassium (Table 2). However, the Kuh-e Sultan Quaternary volcano lies only 100 km east and slightly south of Kuh-e Lar. It would seem unlikely that northward subduction in the Makran region produced alkali volcanism (Kuh-e Lar) in the Oligocene and calc-alkaline volcanism (Kuh-e Sultan) in the Quaternary. Finally, the strongest evidence against alkali volcanism resulting from subduction is the north-south polarity of alkali volcanic outcrops in the Sistan suture zone, as opposed to the post-collision east-west polarity of the subducting trench axis south of the sutured Lut and Afghan blocks (Fig. 1). Another mode of magma genesis must be employed, and such a model should consider the tectonic regime present at the time of magma production.

Although calc-alkaline Quaternary volcanoes border the southern margin of the Lut block, other parts of the block contain scattered exposures of late Cenozoic alkali volcanics (see Berberian & King 1981). These include: (1) east of the Lut block, the Oligo-Miocene (OM^{al}) and Neogene (Ng^v) alkali volcanics exposed in the present map area (Fig. 2) and farther north (Maurizot 1979); (2) north of the Lut block, Neogene alkali basalt, tephrite, and trachyandesite south of Sabzevar (Forster 1968); (3) in the interior of the Lut block, the Qal'eh Hasan Ali tephrites (Milton 1977), the Gandum Beryan analcite basinites (Conrad et al. 1972), and the alkali basalts in the area of Laker Kuh and Kuh-e Nayband (Kluyver et al. 1978). All these alkali volcanics appear in close proximity to major strike-slip faults: the east Lut fault system (Huber 1978), the Great Kavir fault, and the Nayband fault, respectively (Fig. 1).

After closure of the small ocean separating the Lut and Afghan blocks, the tectonic regime in the Sistan suture zone changed from one of northeast subduction with calc-alkaline volcanism to one of east-northeast compression and conjugate strike-slip faulting with alkaline volcanism (Fig. 5). Because of the predominance of right-lateral shear in the late Neogene, the right-lateral strike-slip faults are generally better developed and tend to be more intimately associated with the alkali volcanics (see Fig. 6) than the left-lateral strike-slip members.

The alkali rocks probably were not produced by fractional crystallization of a homogeneous

magma source, since (1) no fractionation trends or magma lineages are obvious from the chemical data, (2) all stratigraphic and plutonic groups contain members that are both saturated and undersaturated with respect to silica, and (3) the overwhelming majority of alkaline rocks are restricted to intermediate and mafic compositions (SiO₂ between 48% and 60%). Partial melting appears to be a more likely method of alkali magma production. The lack of silicic (greater than 60% SiO₂) alkali magma products suggests that the source material is quite mafic; the only obvious candidates for a partial melting source are upper mantle peridotite and the Cretaceous oceanic crust which presumably still marks the basement of the Sistan suture zone. Finally, a mafic source is also indicated from a Neogene alkali volcanic remnant near Zabol which yielded a fairly primitive ⁸⁷Sr/⁸⁶Sr ratio of 0.7049.

Most alkali volcanic provinces (excluding those that are subduction-related) occur in tensional environments such as the East African rift system (King 1970), the Rhine province in western Germany (Carmichael et al. 1974), the Jebel al Abyad province in Saudi Arabia (Baker et al. 1973), and the Basin-Range province of the United States (Leeman & Rogers 1970). In these examples stress is released, apparently allowing partial melting at depth. However, alkali volcanism in the East Iranian Ranges occurred in a compressional environment. As theorized by Uffen (1959) (supported by Uffen & Jessop (1963), and Yoder (1976: 61–63)) failure, coming as a consequence of crustal compression and heating, leads to the release of stress and partial melting. Late Cenozoic failure in the Sistan suture zone resulted in widespread strike-slip faulting. Lithostatic pressure was released and partial melting of either oceanic crust or upper mantle began at depth. The degree of partial melting was probably small (probably <5%; Green (1971), Kay & Gast (1973)) and episodic, as indicated by the high total alkali content of the rocks and the spatial and temporal scatter of the flows and related intrusions.

After each episode of magma generation, successive melts ascended to the surface, commonly using fault planes as conduits for their transport upward. The concentration and ascent of the mafic magma was probably facilitated by the development of local zones of tension along fault planes. The strike-slip faults surrounding and within the Lut block are not perfectly straight and therefore will contain areas of com-

pression and tension along their length. Pakiser (1960) noted that similar regions of relative tension near the ends of strike-slip faults permitted the rise of magma and basaltic volcanism in the Owens Valley of California. Furthermore, many of the strike-slip faults of the East Lut fault system are en echelon and the zones between the ends of adjacent faults may be locally extended (forming pull-apart basins), thus providing a locus for alkali volcanism. Finally, the divergence between right-lateral faults trending north and those trending northeast may have resulted in oblique crustal extension and hence localized volcanism. Similar divergence between the San Andreas fault and more northerly trending strike-slip faults has resulted in oblique crustal extension and Neogene volcanism in the areas of San Francisco and along the coast of northern California (Pilger & Henyey 1979).

Summary and conclusions

From approximately the middle Cretaceous to the Recent the area of the Sistan suture zone has undergone a number of important but relatively short-lived tectonic events: (i) rifting of a large continental mass in the middle Cretaceous produced the Lut and Afghan blocks with an intervening marine basin into which thick piles of marine clastics (flysch) accumulated; (ii) northeast subduction under the Afghan block was well underway by the Maastrichtian; (iii) collision between the Lut block and the Neh complex terminated subduction by about middle Eocene; (iv) continued convergence between the Lut and Afghan blocks resulted in widespread folding and conjugate strike-slip faulting as well as general emergence of the region in the Oligocene and Miocene; (v) major right-lateral strike-slip movements, often concentrated along older faults, resulted from the opposing movements between the Lut and Afghan blocks during the late Miocene (?) to Quaternary (Tirrul et al. in press). These events are summarized in Fig. 5.

Pre-collision magmatism was dominated by calc-alkaline volcanism (KP^v) which we have interpreted as representing early stages in the development of an incipient island-arc. They are thus direct products of subduction tectonics. The relatively minor calc-alkaline mafic intrusions (RS) north of Sefidabeh are probably related to similar events.

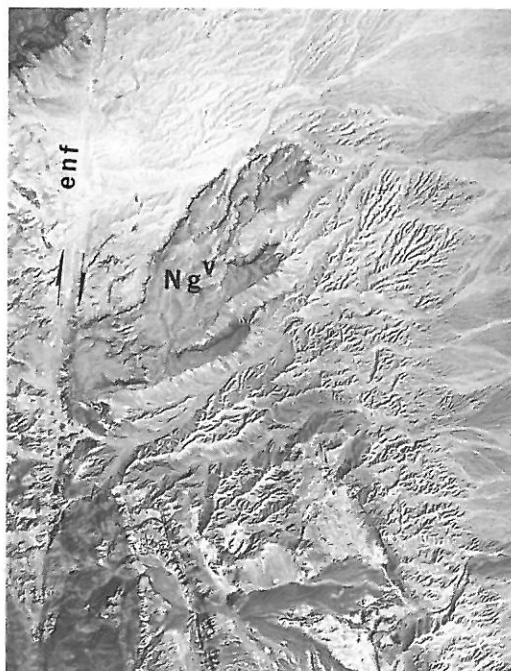


Fig. 6. Air photo approximately 30 km southeast of Nehbandan. East Neh Fault (enf) separates melange of the Neh complex from Sefidabeh basin stratigraphy. In the lower part of photo northeast-dipping ophiolite (dark) lies east of the fault and is unconformably overlain by marine turbidites (light) of the forearc basin. In centre of photo is a Neogene alkali basalt flow remnant (Ng^v) lying above older alluvium and dipping about 15° to the east. Like many other remnants, the basalt lies adjacent to a major transcurrent fault and it gives the appearance of having been extruded from the fault plane.

Immediately after, and possibly during, the collision of the Lut block and the subduction complex, calc-alkaline magmatism was manifested by the development of the large granitic intrusions in the highly deformed accretionary prism (Neh complex). These intrusions have no surface equivalents and are believed to be the anatectic products of widespread melting of trench-fill sediments in the thick accretionary prism.

After subduction ceased as a result of collision, volcanic activity was largely dominated by widespread alkali volcanism (OM^{al}) and minor intrusive complexes that were probably vent areas (KL and KA). This alkali magmatism is closely related to major transcurrent faults which were very important post-collisional structural features. This major phase of volcanism was followed by calc-alkaline volcanism (OM^{ca}) in the north part of the map area and minor calc-alka-

line intrusions (KS, KJ) in the central part of the area. These calc-alkaline products bear no spatial relationship to known major structures and their origin is far from clear since they formed long after subduction had ceased. Their chemistry is compatible with partial melting of sialic material.

The most recent volcanism consists of relatively isolated mafic lavas (Ng^v) most commonly preserved in mesas and buttes adjacent to major right-lateral strike-slip faults (see Fig. 6). These late Miocene to Pliocene flows are weakly alkaline and probably formed in localized zones of extension along or between en echelon fault systems. The upper mantle or an oceanic crust would seem to be the most likely source for these young volcanics. Tirrul et al. (in press) have argued that the late Neogene right-lateral strike-slip faults in the Sistan suture zone may well represent the effects of the indentation of Iran by the Arabian continent. If so then the Ng^v alkali volcanics are an indirect product of this continent-continent collision.

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